DARK INCLUSIONS IN THE REDUCED CV3 CHONDRITE EFREMOVKA: EVIDENCE FOR VARIOUS DEGREES OF AQUEOUS ALTERATION AND THERMAL METAMORPHISM.

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Abstract. We studied the petrography, mineralogy, and bulk oxygen isotopic compositions of three Efremovka dark inclusions (DIs) (E39, E53, E80). These DIs consist of chondrules, CAIs and mineral grains embedded in opaque matrices rich in metal; magnetite is absent and sulfides are either absent (E53, E80) or rare (E39). All coarse-grained components are replaced to various degrees by an Fe-rich phase with olivine composition (Fa_{35-42}), but rich in Al, Ca, Na, Cr, Mn, Na, and S. TEM studies show that the Fe-rich phase consists of abundant fine-grained (<0.2 µm) fayalitic olivine with minor interstitial poorly-crystalline Si-Al-rich material and chlorite. The fayalitic olivines are heavily strained and contain abundant voids. E39 and E80 are surrounded by poorly-developed Ca-rich rims consisting of kirschsteinite. Chondrule pseudomorphs in these DIs and matrix in E80 contain abundant inclusions of Ti-andradite and kirschsteinite (?). We infer that Efremovka DIs experienced various degrees of aqueous alteration and were subsequently metamorphosed resulting in incomplete dehydration, growth of fayalitic olivine and secondary Ca-rich phases. These observations confirm the model of aqueous alteration and dehydration of the oxidized CV3s and their DIs [1].

Introduction. DIs are common in many CV3s, but have been studied in detail mainly in Allende [2-5]. There has been recently a significant interest in the Allende DIs because of their proposed significance for understanding alteration processes that affected CV3 chondrites [1]. Kojima and Tomeoka [6] concluded that Allende DIs were aqueously altered and later thermally metamorphosed. Krot et al. [1] suggested that oxidized CV3s experienced similar alteration processes that resulted in many alteration features previously ascribed to nebular processes. The following studies [7-10] showed that formation of lath-shaped, matrix fayalites and fayalitic olivine rims in Allende and its DIs is consistent with this model. Krot et al. [11] inferred that secondary Ca-rich minerals in the oxidized CV3s, including salite-hedenbergite pyroxenes, wollastonite, andradite, and kirschsteinite, also formed during fluid-assisted metamorphism in the CV3 asteroid. DIs in the reduced CV3s Leoville and Vigarano show textural evidence of aqueous alteration [5,12,13]. Kracher et al. [12] suggested that the Leoville DIs experienced incomplete dehydration, possibly *in situ*. In order to test the model of aqueous alteration-dehydration, we studied three DIs (E39, E53, E80) in the reduced CV3 chondrite Efremovka which are texturally similar to those in Leoville and Vigarano.

Results. The DIs studied show evidence of fragmentation after agglomeration, but before incorporation into Efremovka. Their coarse-grained components are flattened (~1:2) and elongated in the same orientation as chondrules in Efremovka, probably due to shock.

Dark inclusion E53, ~1x2 cm in size, consists of chondrules and CAIs embedded in opaque matrix, rich in metal. No sulfides or magnetite grains are observed. Chondrules, 100-950 µm in apparent diameter, are replaced to various degrees by an Fe-rich phase with the composition of olivine ($Fa_{36\pm5}$), but rich in minor elements (in wt.%, 1.3±0.5 Al_2O_3, 0.5±0.4 Cr_2O_3, 0.4±0.4 CaO, 0.14±0.04 Na_2O, 0.22±0.05 MnO; 0.05-2.7 SO_2). Many chondrules are completely pseudomorphed by the Fe-rich phase, but their original shape and textures are well preserved. The resistance of chondrule minerals to alteration increases in the order low-Ca pyroxene, opaques, plagioclase mesostasis, olivine, spinel, and high-Ca pyroxene. A few low-Ca pyroxene grains that survived alteration are extensively veined by an Al-bearing phyllosilicate, possibly chlorite (in wt.%, 6-18 Al_2O_3, 25-30 SiO_2, 29-40 FeO, 18-27 MgO, 2-4 SO_2, 0.2-0.5 CaO, <0.2 Na_2O). Opaque nodules consist of the Fe-rich phase, Co- and Ni-rich taenite (0.6-3 wt% Co, 28-52 wt.% Ni) and Co-rich (3-10 wt.%) kamacite. Olivine phenocrysts are typically incompletely replaced by the Fe-rich phase; the compositional profiles across forsterite-Fe-rich phase boundaries are very sharp and similar to those in Allende [1]. High-Ca pyroxene grains do not show any evidence of alteration. Cr-spinel grains are rare and show normal metamorphic zoning with $fe=Fe_{tot}/(Fe_{tot}+Mg)$ and $cr=Cr/(Cr+Al)$ ratios increasing towards the rims (fe=0.4-0.7, cr=0.2-0.5). CAIs are small (<500 µm) and abundant; they consist of Al-diopside and fassaite rimming heavily altered cores composed of an Fe-rich phase, which is compositionally similar to those in chondrules; relict grains of melilite and Cr-free spinel (fe=0.2-0.3) are rare.

Dark inclusion E39, ~0.7x1 cm in size, consists of heavily altered chondrules, CAIs and mineral grains embedded in opaque matrix, rich in metal and tiny sulfide grains; the latter are mainly concentrated along the boundary of the DI. Chondrules, 100-500 µm in apparent diameter, are nearly completely pseudomorphed by an Fe-rich phase with an olivine composition ($Fa_{40\pm3}$, in wt.%, 2±0.7 Al_2O_3, 0.6±0.3 Cr_2O_3, 0.4±0.4 CaO, 0.3±0.2 Na_2O, 0.28±0.04 MnO, up to 0.8 SO_2). Relict grains of high-Ca pyroxene are common, olivines are very rare, and low-Ca pyroxenes are absent. Pseudomorphs after chondrule phenocrysts contain small nodules of Ti-andradite (?) with tiny diopside inclusions. Opaque nodules consist of taenite (0.2-2.1 wt.% Co, 31-52 wt.% Ni) and kamacite (0.8-2.5 wt.% Co). Small Cr-spinels with normal metamorphic zoning (fe=0.7-0.9, cr=0.5-0.9) are common. CAIs are small (50-250 µm) and abundant; they are texturally and mineralogically similar to those in E53. The DI is surrounded by a poorly-developed Ca-rich rim consisting of kirschsteinite.

Dark inclusion E80, ~1x2 cm in size, consists of completely altered chondrules and mineral grains with a small amount of opaque matrix, rich in metal. No sulfide or magnetite grains are observed. Chondrules and mineral grains are replaced by an Fe-rich phase with an olivine composition ($Fa_{42\pm4}$, in wt.%, 2.3±1.3 Al_2O_3, 0.7±0.7 Cr_2O_3, 0.6±0.7 CaO, 0.3±0.15 Na_2O, 0.31±0.04 MnO, 0.03-1.5 SO_2). Some chondrule pseudomorphs contain nodules of Ti-andradite (?) with diopside inclusions. There are abundant opaque nodules and small Cr-spinel grains in the chondrules; the latter consist of Co-rich kamacite and wairauite (5-35 wt.% Co) and Ni- and Co-rich taenite (45-50 wt.% Ni, 1-2.5 wt.% Co). Some metal nodules contain very Co-rich taenite (?) (5-10 wt% Co, 45-50 wt.% Ni). Chromites are Fe- and Cr-rich (fe=0.6-0.9, cr=0.6-0.9) and show normal metamorphic zoning. The interstitial matrix material contains small Ca- and Fe-rich grains, possibly andradite or kirschsteinite (?). The DI is surrounded by a poorly-developed Ca-rich rim consisting of kirschsteinite.

TEM studies of several chondrules in E39, E53, and E80 show that the secondary Fe-rich phases consist mainly of abundant fine-grained (<0.2 µm), anhedral to subhedral fayalitic olivine, with minor interstitial poorly-crystalline Si-Al-rich material and chlorite. Fayalitic olivines are heavily strained and contain abundant voids similarly to those in Allende [10]. In contrast to Allende fayalite, spinel inclusions are rare; sulfide inclusions are not observed.

Bulk oxygen isotopic compositions of Efremovka DIs are similar to the previously analyzed DIs in Leoville and Vigarano [5] and are consistent with their aqueous alteration and with E39 (ä^{18}O=12.7, ä^{17}O=4.87) being more heavily altered than E53 (ä^{18}O=9.79, ä^{17}O=4.09).

Bulk chemical analyses of E53 and E80 by INAA and I-Xe study of E39 are in progress.

Discussion. The textural and mineralogical observations indicate that primary silicates in the Efremovka DIs are replaced by the Fe-rich phase composed of fayalitic olivine, poorly-crystalline Si-, Al-rich material and chlorite. The degree of alteration is anticorrelated with the abundance of relict primary minerals in chondrules and increases in the order E53, E39, and E80. The replacement process is completely pseudomorphic and unequivocally preserves the outline of primary chondrule minerals; it involved significant transport of Al, Mg, Fe, and Ca. The absence of sulfide grains in E53 and E80 probably indicate that open-system alteration operated and resulted in the nearly complete loss of S.

We infer that the Efremovka DIs experienced various degrees of aqueous alteration and were subsequently metamorphosed, at least partly *in situ*, resulting in their incomplete dehydration and growth of fayalitic olivine, Ti-andradite and kirschsteinite. The aqueous alteration is strongly supported by the presence of relict chlorite left after dehydration, which was probably stable to higher metamorphic temperatures. High Al contents in the secondary Fe-rich phase indicate that the precursor phyllosilicate for the fayalitic olivines was probably serpentine. Although the alteration processes that affected Efremovka DIs are very similar to those inferred for Allende DIs [1], there are some differences as well. The chondrule silicates in Efremovka DIs are replaced by fine-grained, anhedral to subhedral fayalitic olivines, whereas in Allende DIs tend to be much coarser-grained and either platy or tabular in morphology. It seems possible that the initial heating of the metamorphic event for the Efremovka DIs was more rapid resulting in a very high nucleation rates, nucleation site saturation and formation of many small crystals. The small grain size also helps account for the lack or low abundance of inclusions in the fayalitic olivine. For the Allende DIs, the nucleation rate may have been lower, such that fewer grains formed, but they grew to larger sizes. However, the growth rate must have been reasonably fast in order to include abundant fine-grained chromite, hercynite, pentlandite, and ilmenite crystals [10]. The presence of well-developed Ca-rich rims around many Allende DIs [11] and poorly-developed Ca-rich rims around Efremovka DIs is also consistent with the longer duration of the metamorphic event for the former.

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